Applied Mathematical Modelling 000 (2016) 1–8

Contents lists available at ScienceDirect

Applied Mathematical Modelling

journal homepage: www.elsevier.com/locate/apm

Photothermal response of polymer microcantilever with metal coating in fluids

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ARTICLE INFO

Article history:
Received 9 July 2015
Revised 12 July 2016
Accepted 15 September 2016
Available online xxx

Keywords:
Photothermal
Vibration
Polymer microcantilevers
Fluids

ABSTRACT

Cantilever beams are used as sensors in a great variety of applications. It is a promising research to study the vibration characteristics of microcantilever for biological and chemical detections. In this paper, a (a a) theoretical model was used to calculate the photothermal vibration frequency spectra of coating polymer microcantilever, which immersed in fluids and excited by an intensity-modulated laser beam. The comparison was made among the response of vibration in different fluids. Theoretical analysis demonstrated that a great distortion occurred to the vibration frequency spectra due to the high density and viscosity of liquids. In addition, it can be concluded from theoretical calculation that the coating has significant effect on the dynamic response of microcantilever.

1. Introduction

Microcantilevers have been used in many fields as sensors to detect small changes in mass, density, stress, temperature, etc. Importantly, many of these sensors are performed in fluid environment (gas and liquid) [1–3], which has been shown to significantly affect the dynamic response of the cantilever. Due to its significance in a wide range of practical application, the study of vibrating cantilever immersed in fluid has an extensive application and received considerable attention, both theoretically [4–11] and experimentally [5–16]. Sader presented a detailed theoretical analysis of a cantilever beam immersed in a viscous fluid and excited by an arbitrary driving force [4]. Using the fluctuation–dissipation theorem, Paul and Cross gave the stochastic response of nanoscale cantilever [5]. Basak et al. computationally analyzed microcantilever vibrating in viscous fluids using a three-dimensional, finite element fluid-structure interaction model [6]. Dorignac et al. derived an exact expression for the spectral density of displacement and a linear approxiamation for resonance frequency shift using the fluctuation–dissipation theorem [7]. A TB/Stokes fluid resistance model was introduced by Schultz et al. [8]] to investigate the effects of the excitation method and detection scheme on the dynamic response of lateral-mode microcantilevers. Dufour et al. studied the effect of hydrodynamic force on microcantilever vibrations by proving an overview of the relevant hydrodynamic force equations for three different modes of vibration [9]. Wang et al. reported a simplified aeroelastic model to establish a fluid-structure coupling vibration model for microcantilever sensors [10]. Incorporating viscous fluid effects and

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http://dx.doi.org/10.1016/j.apm.2016.09.014
0307-904X/

Timoshenko beam effects, a new model is developed by Schultz et al. to study the lateral-mode vibration of microcantilever-based sensors in viscous fluids [11]. Dufour et al. [12] presented two methods to measure the hydrodynamic force exerted by a confined fluid and dynamic spectrum by the surrounding fluid on the microcantilever. Schultz et al. [13] examined the material property to the response of microcantilever immersed in liquids. Steffens et al. studied microcantielver sensors with doped polyaniline for the detection of water vapor [14]. In combination with the pump-probe technique or spin resonance spectrum, Wu and Zhu [15] proposed a realistic, feasible, and exact way to measure the cantilever frequency in a hybrid spin-micromechanical cantilever system. Qiu et al. [16] experimentally studied the hydrodynamic loading effect on a flexural vibrating microcantilever immersed in six different viscous compressible gases. The fluid will not only result in decrease of the resonance frequencies, but also lead to reduction of the peak amplitude, lower quality factors and slow down the steepness of phase response [17].

Many conventional microcantilevers used as sensors are fabricated on a silicon substrate. Manufacturing of polymer components of micrometer-size by mass fabrication is an emerging technology. Several attempts have been made to replace Si microcantilevers in sensors for biochemical applications by polymer-based microstructures [18–21]. Compared to conventional silicon or silicon nitride cantilevers, polymer micro cantilevers have very high compliance, sensitivity, robustness and durability. Also, this kind of cantilevers can operate in transparent and opaque liquid environments. Therefore polymer cantilever highly suited for sensing applications. Seena et al. [22] fabricated piezoresistive SU-8 microcantilevers using SU-8/carbon black (CB) composite and presented results on the electromechanical characterization and biofunctionalization of the cantilever structures for biochemical sensing applications. Lee et al. [23] presented a polymer microcantilever platform for handling massive microparticles or cells using combined forces induced by dielelectrophoresis and gravity. A new strategy for the label-free monitoring of yeast cell growth and its interaction with drugs using simple bending-mode of polymer microcantilever biosensors was presented by Liu et al. [24]. Shang et al. [25] studied the fabrication and characterization of a polymer/metal bimorph microcantielver for ultrasensitive thermal sensing. Patil et al. [26 and 27] demonstrated a novel, compact and inexpensive polymer nano-compostie piezoresistive microcantilever sensor platform for the measurement of relative humidity and soil moisture, and explosive vapor. Ray et al. [28] developed a kind of polymer (SU8) microcantilever strain sensor for vapour phase explosive detection applications.

There are many methods to drive a microstructure to vibrate, like piezoelectric [29], electromechanical [30], photoacoustic (PA) [31] and photothermal (PT) [32,33], etc. PT science and technology have developed many new methods to investigation of semiconductors(semiconductor) and microelectronic structures. Due to its merits of noncontact and nondestructive, these methods are widely used as a detection way in microelectromechanical system (MEMS) and nanoelectromechanical system (NEMS), especially in situations where other techniques are not useful. Another merit of optical excitation method is this method produces a frequency response unaffected by spurious contributions of noise from mechanical coupling through liquids, thus providing an opportunity to explore details of hydrodynamic and fluid systems [34]. In photothermal method, the loading type is critical for understanding the deflection shape and resonance frequency. Evans and Craig [35] gave very good work on the relationship between deflection and loading types in detail.

In this work, a focused laser excitation was considered as a point source act on a microcantilever. A theoretical model is established for photothermal response of a polymer microcantilever with a metal coating immersed (immerging) in fluids. Using the theoretical model, the external force and the temperature profile of the polymer microcantilever under focused laser excitation were obtained. Also, the deflection expression of the microcantilever was given analytically and the fluidic environment and the effects of different coating to the response of microcantilever were shown graphically.

2. Theoretical models

PT effect can be important as driven mechanisms for micromechanical structures, especially for a microcantilever. The vibration of microcantilever can be generated by a modulated laser. The optomechanical response of micromechanical cantilevers as a consequence of the PT modulation has been used primarily as a single wavelength technique to drive a cantilever at or near its resonance frequency for dynamic mode and as a driving mechanism for nanomechanical oscillators.

When a polymer microcantilever is optically excited, due to absorption this optical energy in response to the temperature variations, thermoelastic effects will cause the vibration of the microcantilever. The theoretical study of the elastic vibration of a polymer microcantilever during photothermal process includes quantitative accounts of the temperature field, T and elasic field, $\boldsymbol{u}(\boldsymbol{r}, t)$. For a medium with isotropic and homogeneous properties, two steps are needed to get the frequency spectra for the vibration microcantilever. First step is to calculate the response of temperature field due to the local periodic laser heat source. Second step is to compute the dynamical deflection field caused by the external applied load.

2.1. Temperature profile

The governing equation of absolute temperature $T(x, t)$ for a microcantilever with metal coating is given as [36]

$$\frac{\partial T(x,t)}{\partial t} = K\frac{\partial^2 T(x,t)}{\partial x^2} - \beta T(x,t), \tag{1}$$